Wei Zhu
Bell Laboratories, Lucent Technologies

Wei Zhu is a member of technical staff in the Physical Science Division at Bell Laboratories, Lucent Technologies. He obtained his BS and MS degrees in Metallurgy, and his Ph.D. degree in Solid State Science from Pennsylvania Sate University. Before joining Bell labs, he spent three years as a visiting assistant professor at North Carolina State University. He organized the first materials research society symposium on vacuum microelectronics and edited two books on the subject. He is a member of American Vacuum Society, Materials Research Society and Society for Information Displays. His main research area is in carbon-based materials, including their synthesis, structures, properties and applications. Other research interests include thin film synthesis of wide band gap materials, cold cathode materials and devices and high density interconnect materials. He has given many invited speeches on these various research topics. He has over 40 publications and holds more than 20 patents. Phone 908-582-7659, Fax 908-582-4868, email wzhu@bell-labs.com

Lucent Technologies
Bell Labs Innovations

Carbon Nanotubes: An Industrial Perspective

W. Zhu

Bell Laboratories

Lucent Technologies

Murray Hill, NJ

March 1999

Lucent Technologies
Bell Labs Innovations

Content

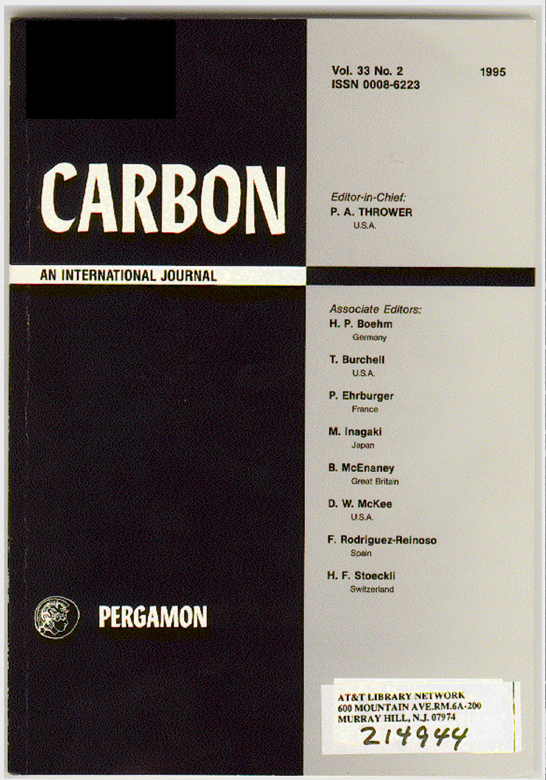
- Background
- Survey of Potential Applications
- Carbon-Based Vacuum Microelectronic Devices
  - Review of emission physics
  - Diamond vs. CNT field emitters
- Summary

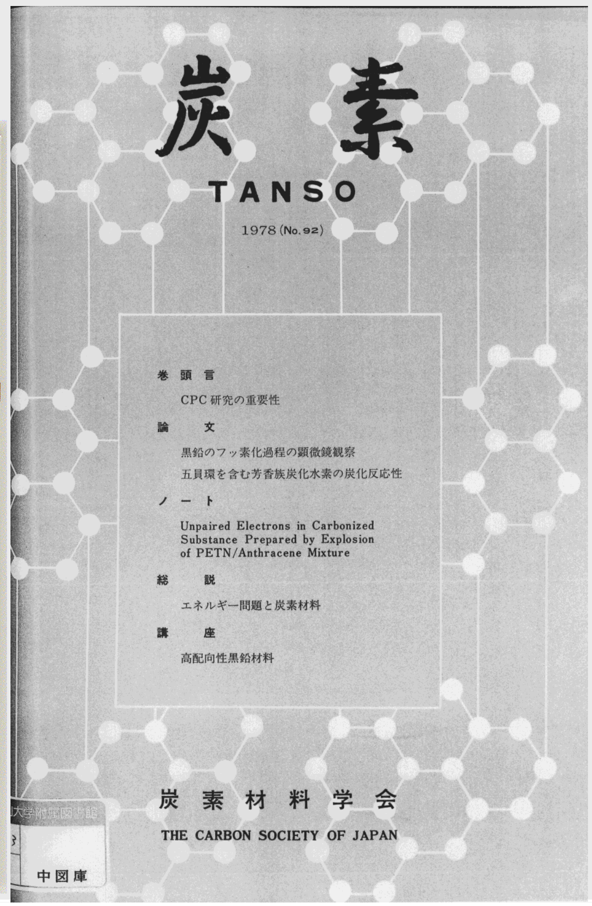
Lucent Technologies
Bell Labs Innovations

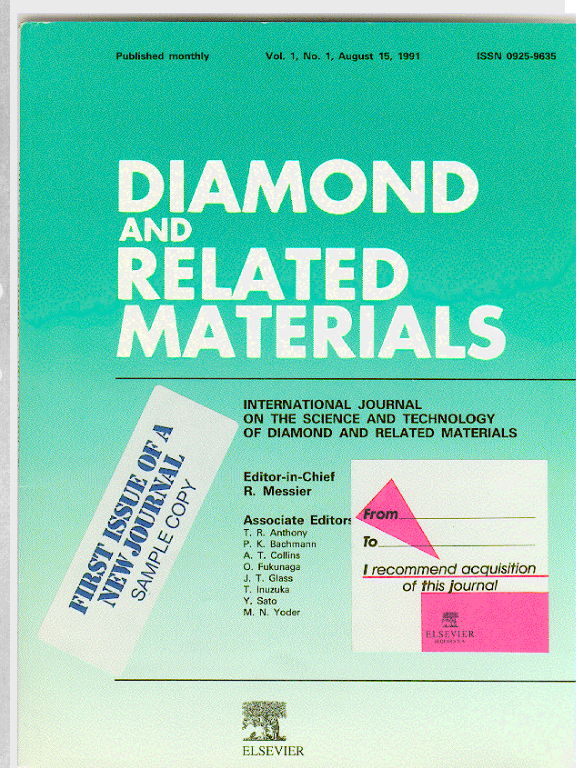
The Carbon Family

- Varieties of Solid State Forms
  - diamond, graphite, carbyne, C_{60}, nanotubes, DLC, amorphous carbon, glassy carbon, ...
- Extreme Physical Properties
  - spanning the whole spectra in electrical, optical, thermal and mechanical properties.
    - highest strength fiber (carbon fibers)
    - best lubricant (graphite)
    - costliest stone, hardest material and best thermal conductor (diamond)
    - bast gas adsorber (activated charcoal)
    - best helium gas barrier (vitreous carbon)

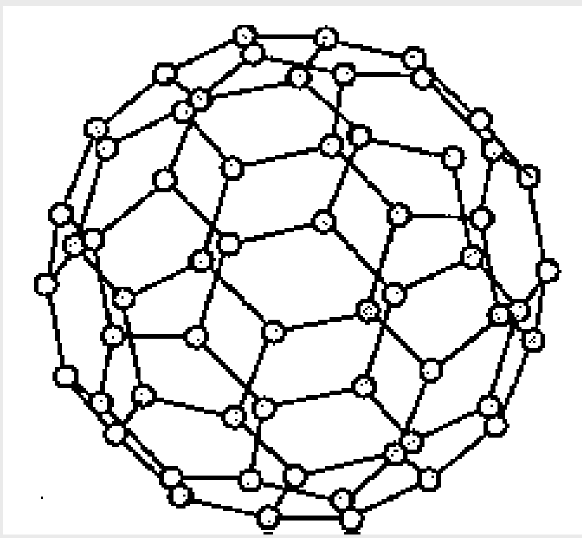
Carbon and Related Journals

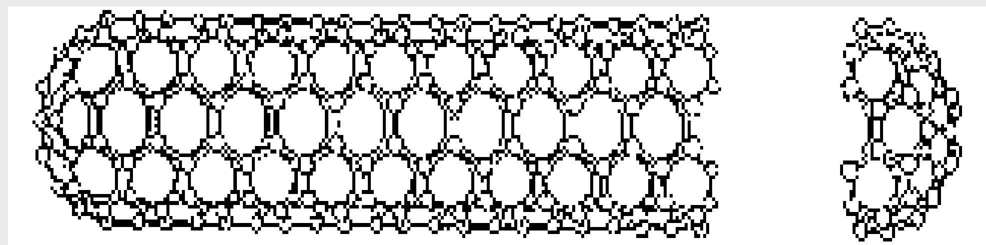






Fullerenes and Nanotubes





$\underline{C_{60}}$ -

dominantly sp^2 bonding

truncated icosahedron

fcc/sc crystals

Nanotube

sp^2 bonding dominant

d (tube diameter) and θ (chiral angle)

Potential Applications of CNTs

- Carbon-Based Nanotechnology
  - molecular engineering or designing
  - nanoscale devices, robots, sensors, machines, etc. are too appealing to be ignored.
- CNT-Reinforced Composites
- Battery Electrode and Energy Storage
- Nanoelectronics
- Vacuum Microelectronics Devices

Lucent Technologies
Bell Labs Innovations

Composites

- Reinforced polymers, metals and ceramics.
  - CNT-plastic composites for absorption of electromagnetic radiation - Stealth technology.
- Conductive or anisotropically conductive composites.
- Molecular composites.
- Issues
  - volume production of high quality CNTs.
  - target price (<$50/kg)

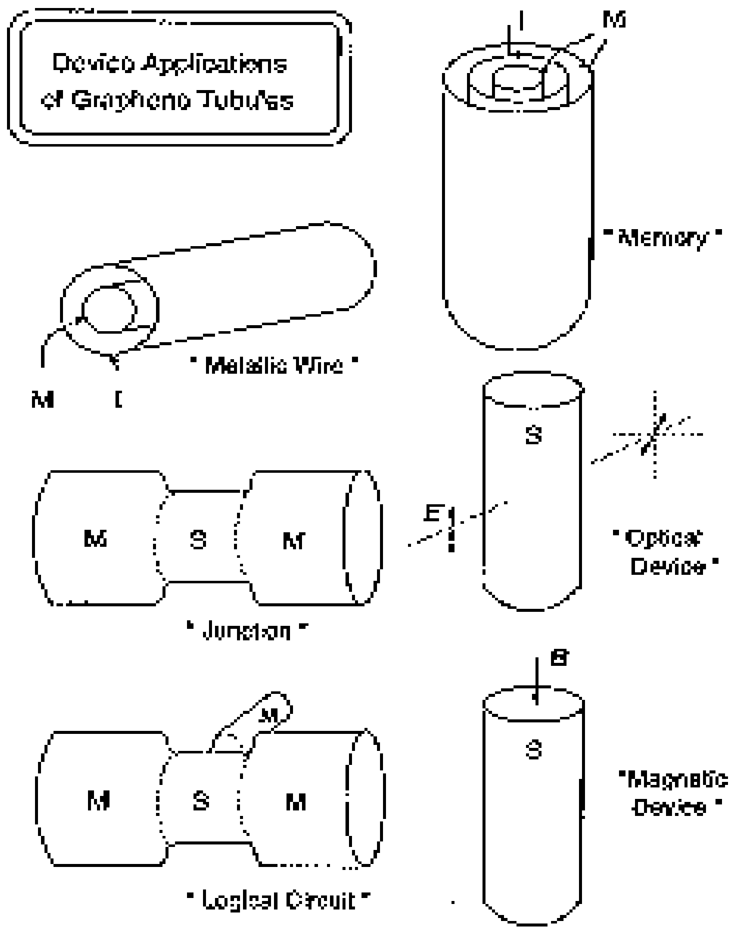
Battery Electrode and Energy Storage

- Li uptake and intercalation
  - Li ion battery
- Hydrogen absorption
  - hydrogen/air fuel cell
- Supercapacitors
  - high frequency pulsing, high power density.
- Issues
  - fundamental mechanisms unclear.

Nanoelectronics

- Device Components (diode, transistor, capacitor)
  - chirality and diameter $\Rightarrow$ electronic properties
  - small band-gap, quantum ballistic transport, single e^- transistor
  - sub-MEMS
  - nanoprobe for metrology diagnostics
- Interconnects
  - nanowiring
- Issues
  - controlled and reproducible growth with tunable diameter and helicity.
  - controlled doping.

Nanoelectronics



From: *Science of Fullerenes and Carbon Nanotubes*, by M. S. Dresselhaus, G. Dresselhaus, and P. C. Eklund, ISBN# 0122218205, pp. 903

Vacuum Microelectronic Devices

- Field emission, flat panel displays
- Microwave power amplifier tubes (traveling wave tube/klystron)
- Vacuum field emission triode
- Electron source (for microscope, e-beam litho, etc.)

Lucent Technologies
Bell Labs Innovations

Flat Panel Displays

- LCD/AMLCD
  - light valves that modulate the transmitted luminance of a white backlight through color filters.
  - dominant in all current applications.
- Emissive Displays (FED, PDP, EL, OLED)
  - light emission from phosphor pixels after electric or photonic switching.
  - bright, rugged, wide viewing angle, scalable to large size.
  - key to success: manufacturing cost.

Lucent Technologies
Bell Labs Innovations

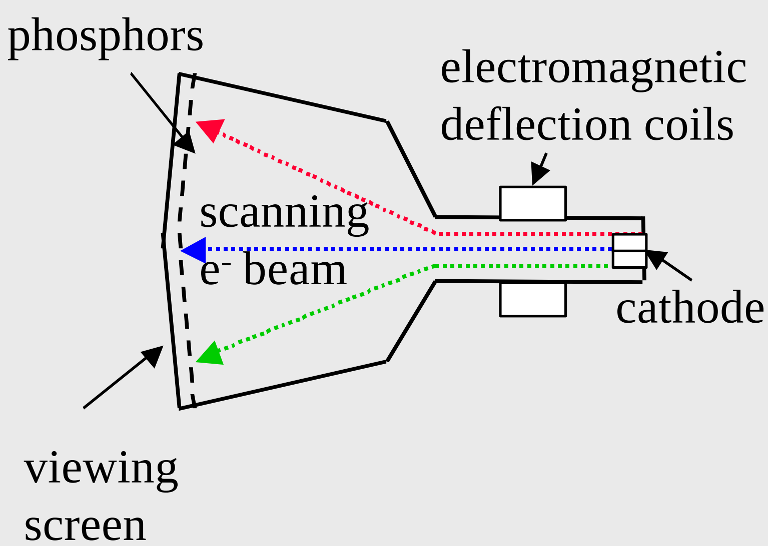
Field Emission Displays

5.6” diagonal,
full color,
1/4 VGA
brightness: 300 cd/m^2

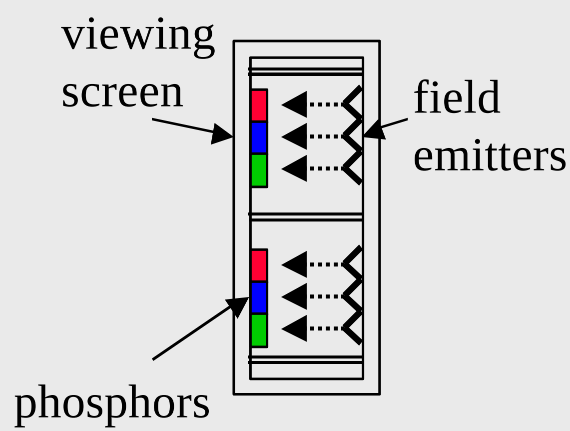
Courtesy of
Motorola, Inc.

Lucent Technologies
Bell Labs Innovations

Field Emission Display & CRT



CRT



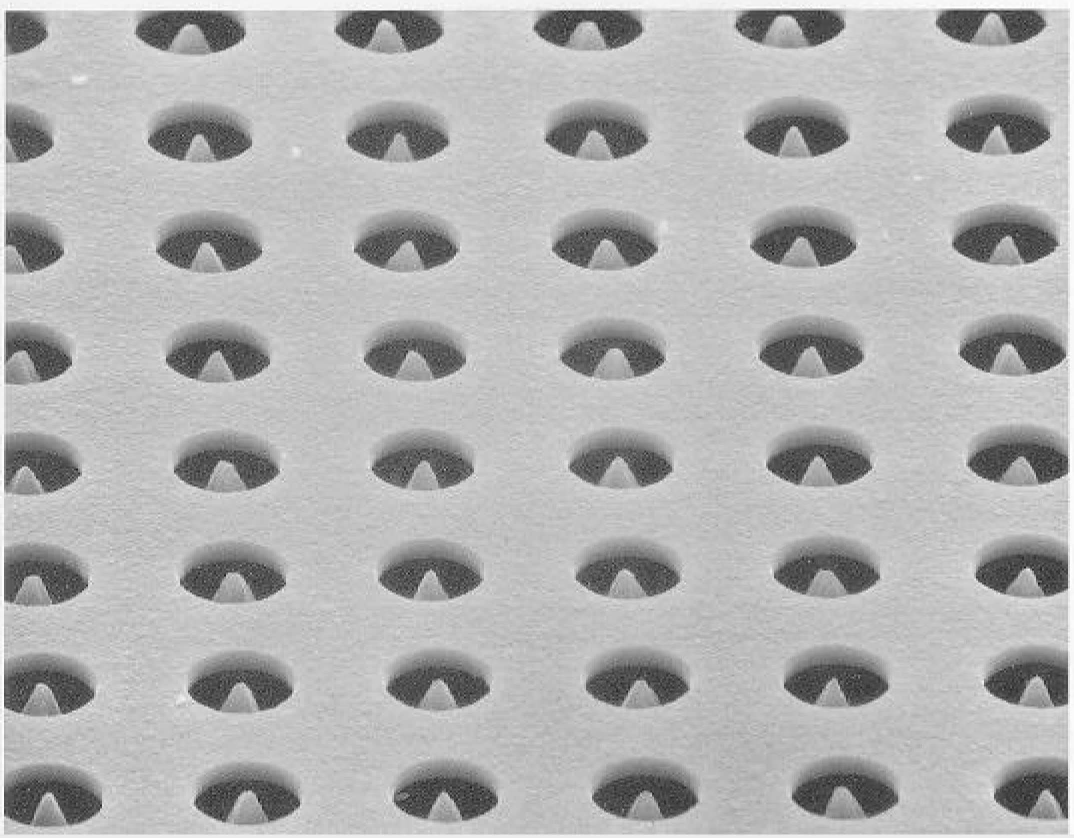
FED

Lucent Technologies
Bell Labs Innovations

Cathode Requirements for FED

- High emission uniformity ($>10^6$ sites/cm^2).
  - in-line impedance (resistor or capacitor) required
- Moderate current density (~10 mA/cm^2).
- Large area processing.
- Low-cost manufacturability.
  - fine-line lithography-free fabrication.

Field Emitter Arrays in FED

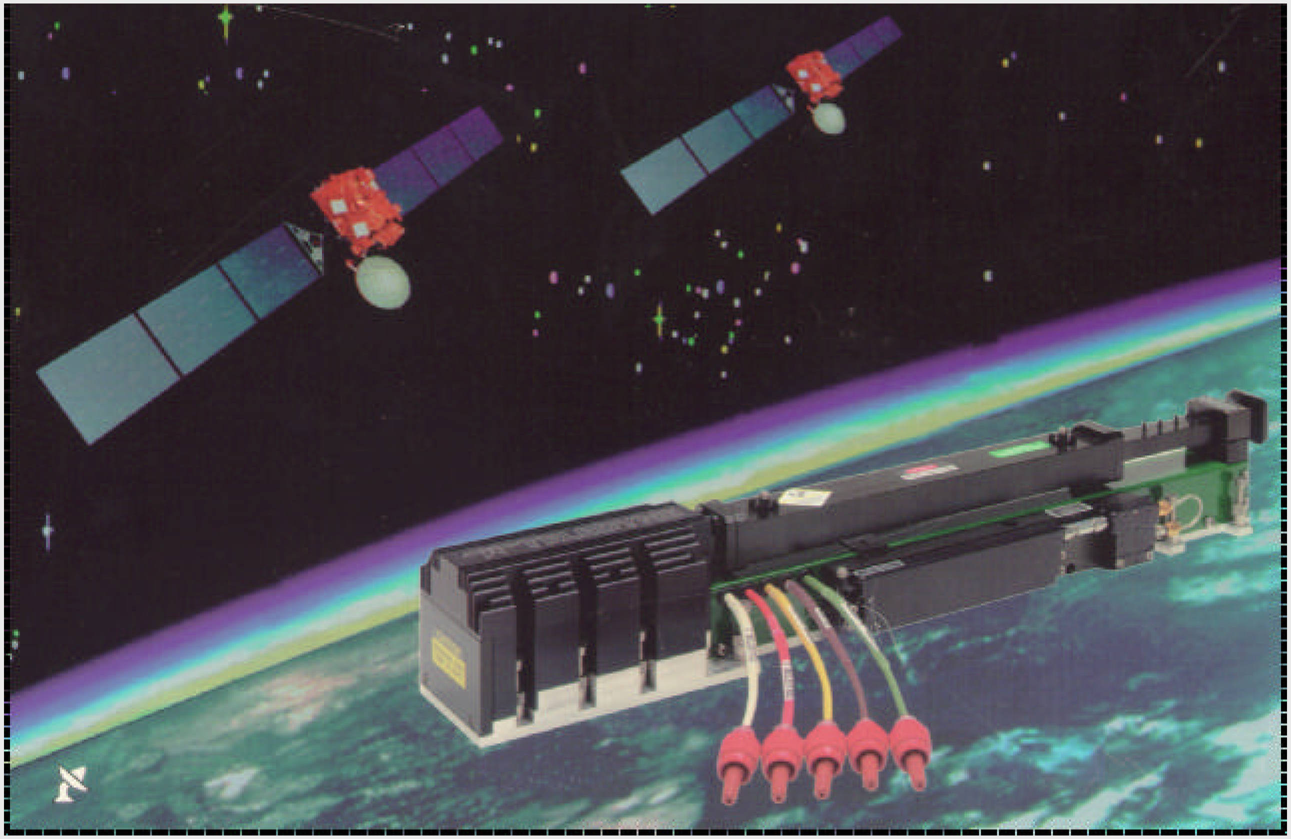


Courtesy of Futaba Co.

Microwave Tube Amplifier

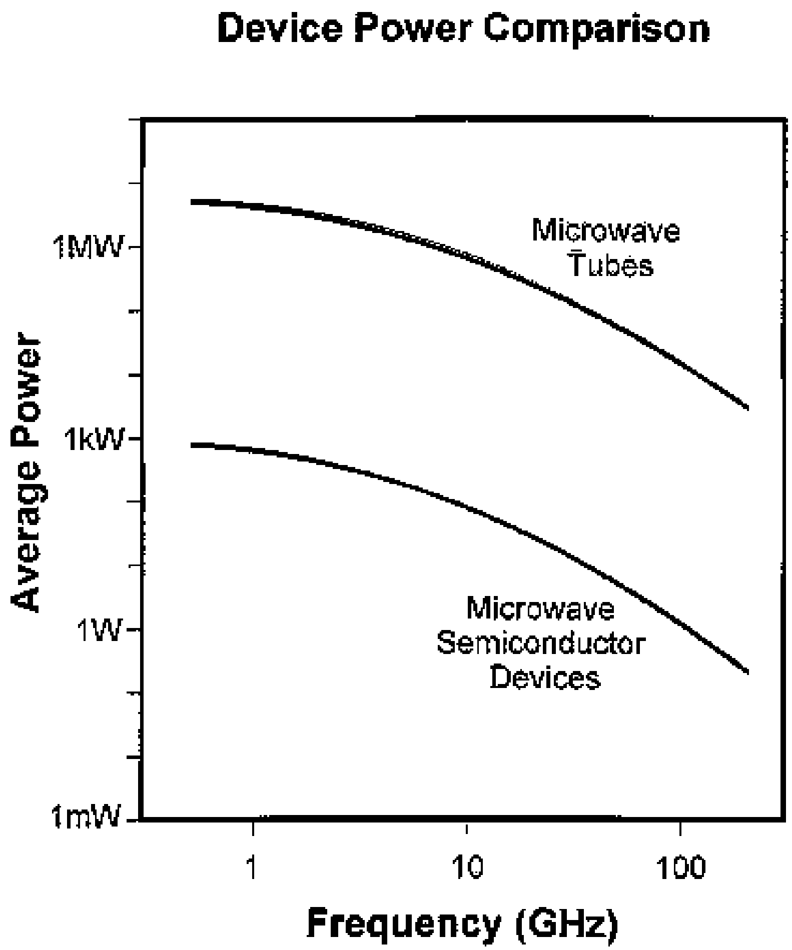
- Indispensable in communications, EW and radar, and instrumentation.
- Advantages of cold cathode microwave tube amplifier.
  - high power (~100 W).
  - radiation hard.

Microwave Tube Amplifier - TWT



Courtesy of Teledyne Electronic Technology

Vacuum Tubes vs. Semiconductor Devices



Lucent Technologies
Bell Labs Innovations

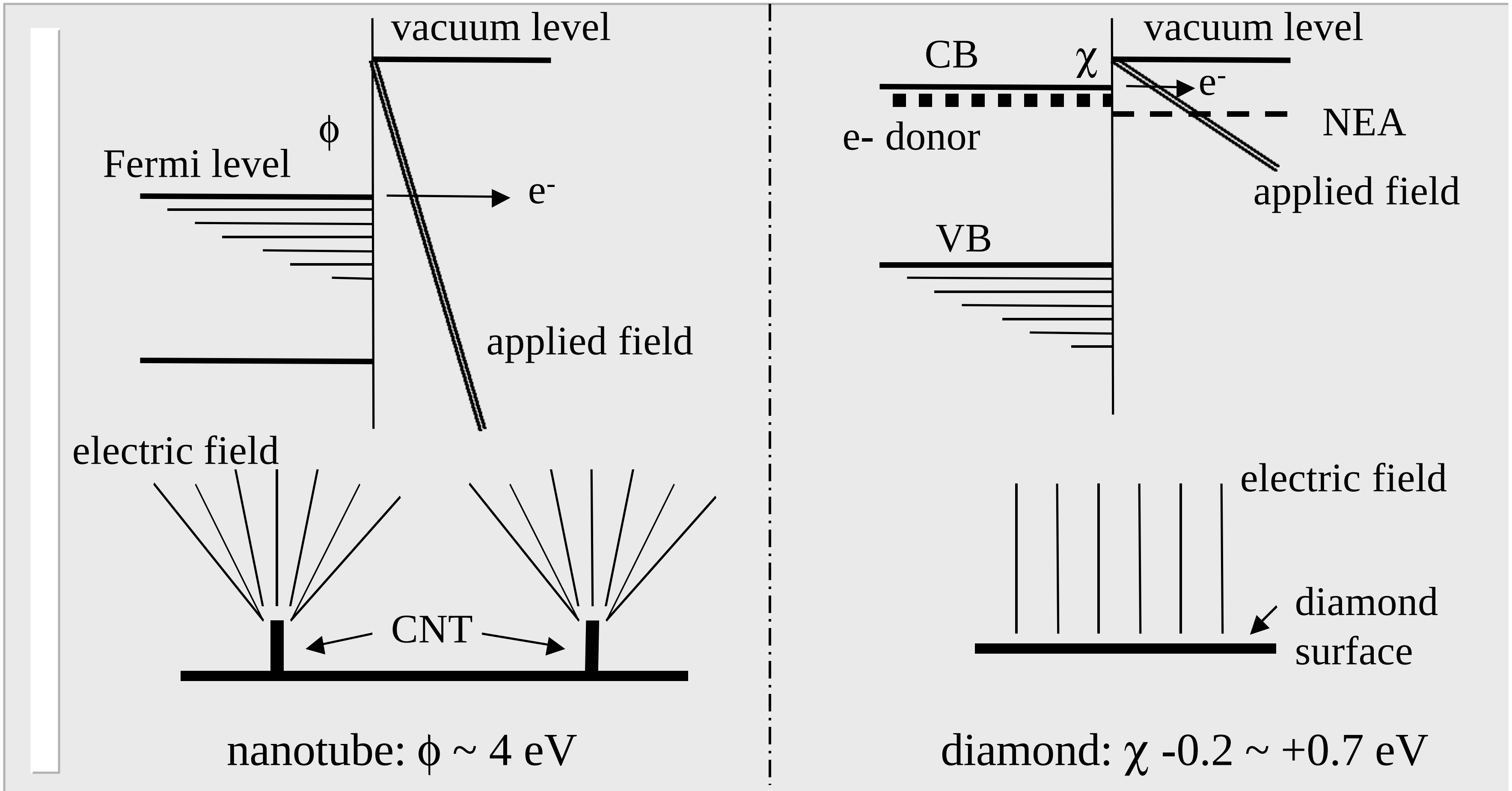
Microwave Amplifier Tube

- Advantages of vacuum tube over semiconductor device
  - higher power but smaller in size (for equivalent power).
  - broad bandwidth (30-120%) and high gain (30-50 dB).
  - radiation resistant.
- Advantages of cold cathode tube over hot cathode tube
  - instantaneous turn-on.
  - shorter length / elimination of cooling auxiliaries.
  - less power.
  - lower noise.
  - longer lifetime.

Cathode Requirements for Microwave Tube Amplifier

- Large current capability (>500mA/cm^2).
- High beam quality (energy/velocity spread, divergence/convergence, etc.)
- Long lifetime (>10,000 hours).

Carbon Based Field Emitter



Lucent Technologies
Bell Labs Innovations

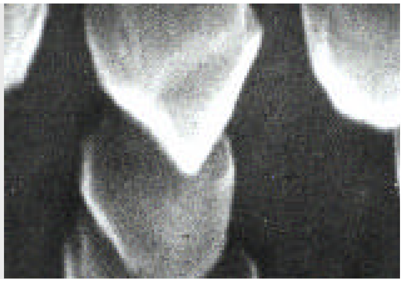
Diamond Field Emitter

- Attributes
  - Low/negative electron affinity.
  - "Flat cathode" - no need for microtip fabrication.
  - Chemically and mechanically robust.
- Results
  - good mechanistic understanding (roles of defects)
  - low emission threshold field (5-10 V/μm for 10 mA/cm^2)
  - limited durability at high current densities (>30 mA/cm^2)
  - low emission site density (10^4/cm^2)

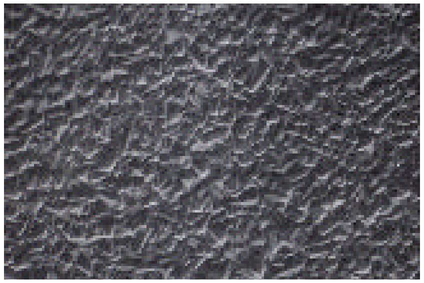
Diamond Emitters

islands | islands | continuous film

4 μm



400 nm

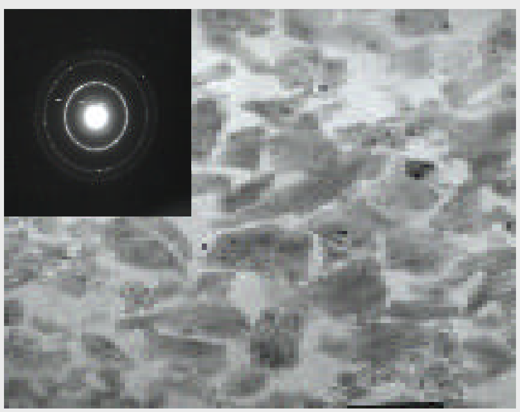


2 μm

Nano-Structured Diamond Emitter

SEM

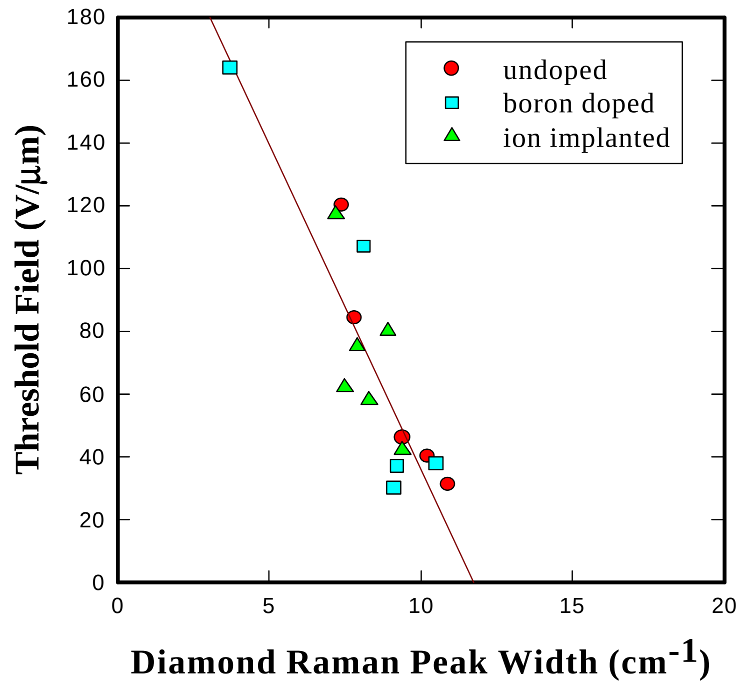
300 nm



TEM

50 nm

Defects in undoped diamond makes low field electron emission possible.

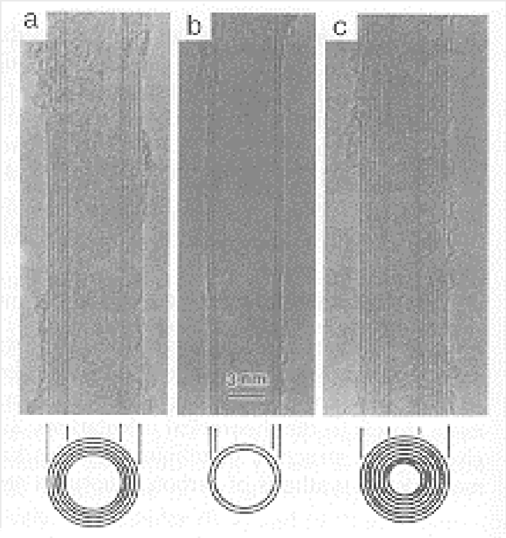


From: Zhu et al. *Science*, vol 282, p 1471, 1998.

Lucent Technologies
Bell Labs Innovations

Nanotubes Field Emitters

- Properties
  - One-dimensional nanostructure (AR>1,000).
  - Small tip radii of curvature (~1-10 nm).
  - Mechanical robustness and chemical stability.

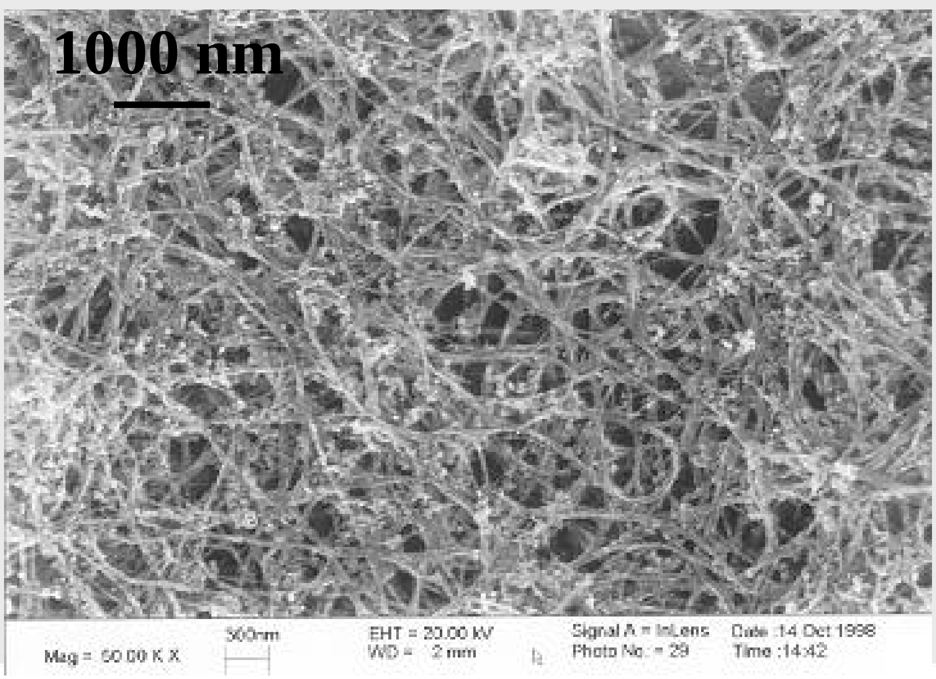


Lucent Technologies
Bell Labs Innovations

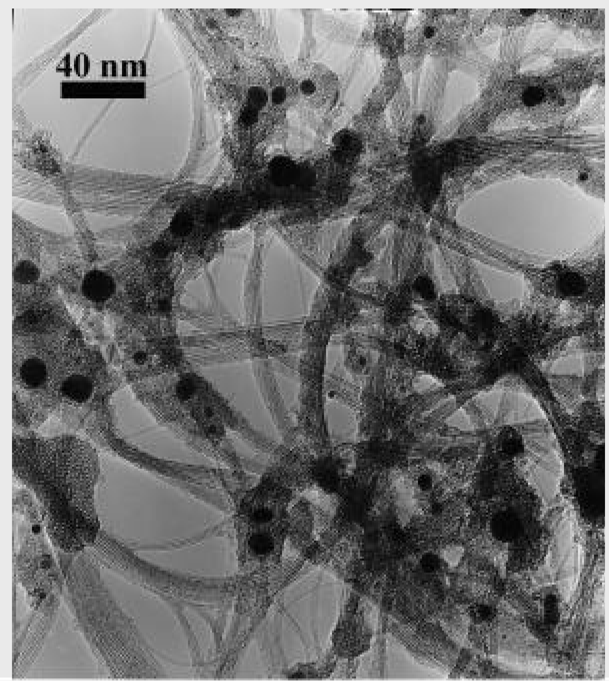
Carbon Nanotubes Field Emitters

Randomly Oriented SWNT Bundles (10-30 nm in diameter)

SEM

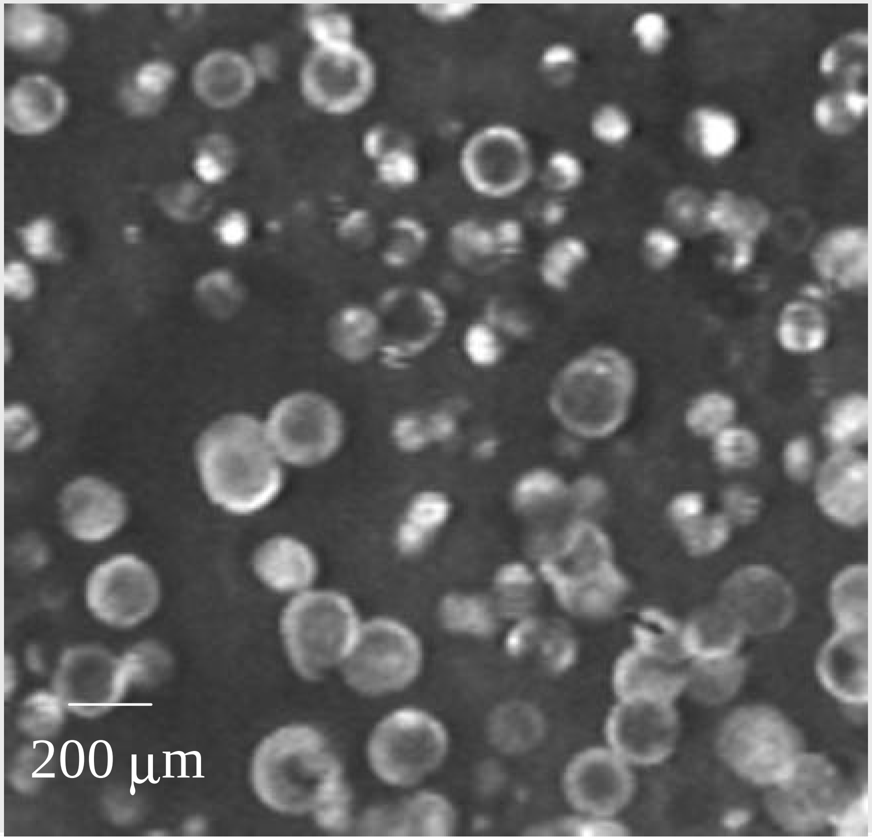


TEM



CNT Field Emitters

Field Emission Pattern



Lucent Technologies
Bell Labs Innovations

Nanotube Field Emitter

- Results and Issues
  - high J (~4 A/cm^2) from random SWNTs
  - need to improve emission site density (10^3 $/cm^2$)
    - hot spots
    - nanotube alignment would be helpful
  - need to improve film adhesion.
    - premature failure

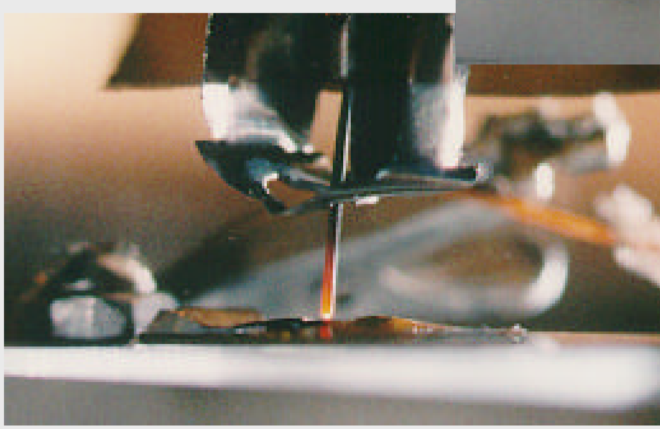
Lucent Technologies
Bell Labs Innovations

Carbon Nanotube Field Emitters

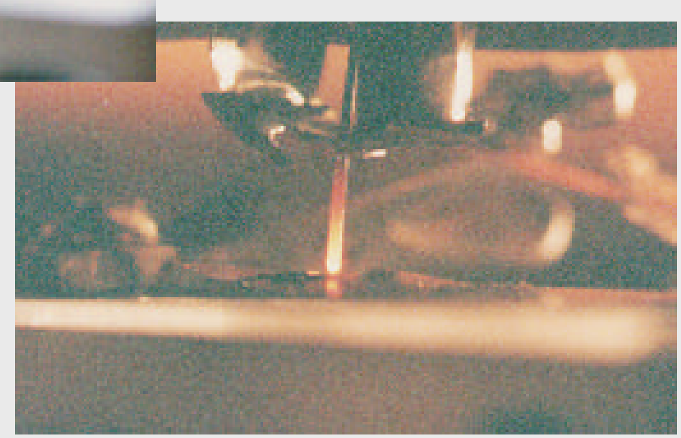
- High Current DensityEmission

(0.3 A/cm^2)

(0.9 A/cm^2)



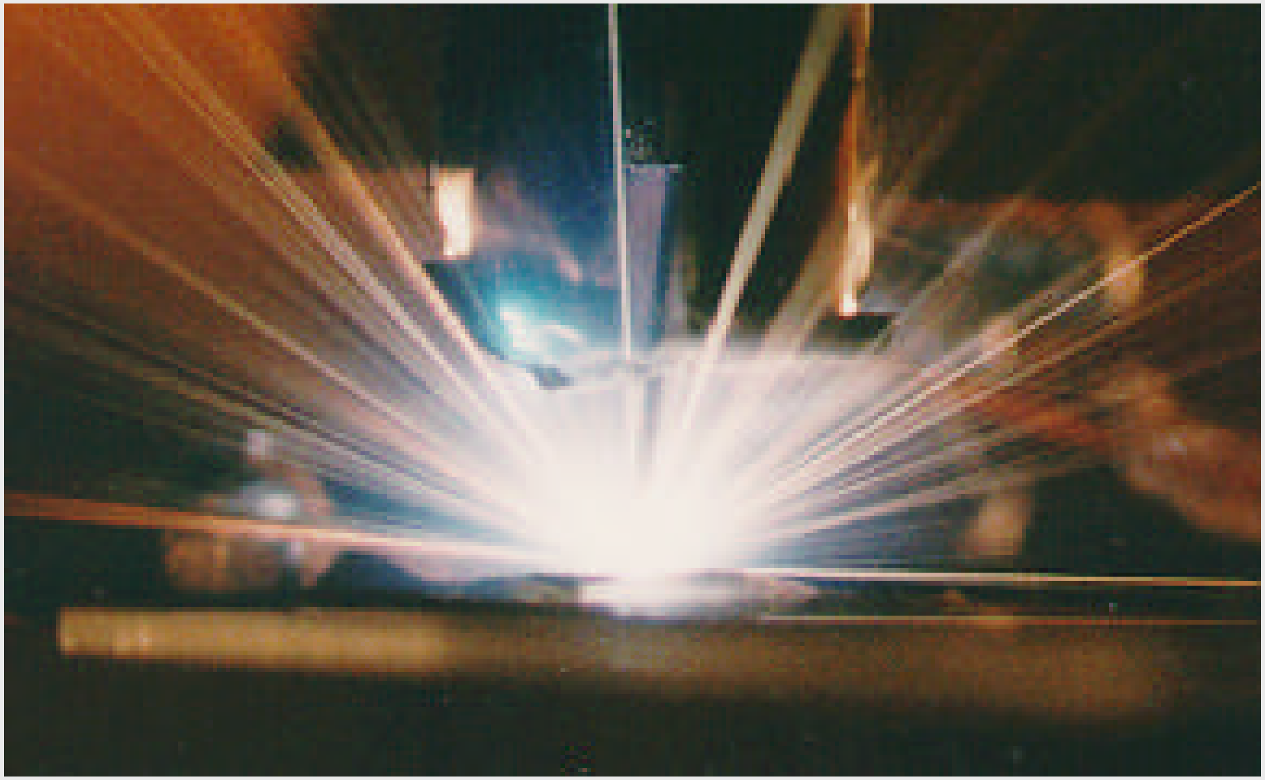
(1.5A/cm^2)



Lucent Technologies
Bell Labs Innovations

Carbon Nanotube Emitters

Arc from Nanotube Emitter



Lucent Technologies
Bell Labs Innovations

Cold Cathodes

Comparison of emission field (@10 mA/cm^2)

Material	E (V/μm)
Mo or Si tips	50-100
P-type diamond	160
undoped, defective CVD diamond	30-120
DLC	20-40
Cs-coated diamond	20-30
graphite powders (<1 μm)	17
nano-structured diamond	5-10 (unstable at >30 mA/cm^2)
carbon nanotubes	3-5

Lucent Technologies
Bell Labs Innovations

Summary

- Carbon nanotubes are
  - unique.
  - versatile.
  - enabling.
- Near term applications are likely in composites and VME.

Lucent Technologies
Bell Labs Innovations

Acknowledgments

- *G. P. Kochanski* and *S. Jin*

  Bell Labs, Lucent Technologies, Murray Hill, NJ
- *C. Bower* and *O. Zhou*

  University of North Carolina, Chapel Hill, NC